GIS-BASED EVALUATION OF ACTUAL AND POTENTIAL LAND SUITABILITY FOR POTATO (*Solanum tuberosum L.*) CULTIVATION IN THE POST-ERUPTION LANDSCAPE OF MOUNT SINABUNG, INDONESIA

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ABSTRACT

Potato (Solanum tuberosum L.) is a high-value horticultural crop whose productivity depends strongly on land suitability, particularly in volcanic regions where repeated eruptions alter soil properties and landscape characteristics. Evaluating land suitability is therefore essential for identifying cultivation constraints and developing sustainable land management strategies. This study assessed the actual and potential land suitability for potato cultivation in the post-eruption area of Mount Sinabung, North Sumatra, Indonesia, using a Geographic Information System (GIS)-based land evaluation approach integrated with the FAO matching framework. Land Mapping Units (LMUs) were delineated through the overlay of soil type, elevation, and slope maps, followed by field surveys and laboratory analyses of soil physical and chemical properties. Thirteen LMUs were identified, with LMU 1 (Sigarang-garang Village) and LMU 2 (Sukanalu Village) representing the eruption-affected agricultural areas. Under current conditions, LMU 1 was classified as Not Suitable (N) because of severe erosion hazards, whereas LMU 2 was classified as Marginally Suitable (S3), primarily constrained by temperature and nutrient retention. Following the implementation of feasible land improvement measures, including soil conservation, liming, and organic matter application, the potential suitability of LMU 1 improved to S3, while LMU 2 remained S3 due to persistent climatic and land preparation constraints. The findings indicate that erosion hazard and nutrient retention are manageable limiting factors, whereas temperature and topographic conditions remain relatively permanent constraints. This study demonstrates the value of integrating GIS, field observations, laboratory analyses, and FAO land evaluation for supporting evidence-based agricultural planning and sustainable potato production in volcanic post-eruption landscapes.

Keywords: *Geographic Information System, Land Suitability, Mount Sinabung, Potato, Volcanic Landscape.*

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the world's most important horticultural commodities because of its high economic value and strategic role in supporting food security. Potato productivity is strongly influenced by land characteristics, particularly soil physical and chemical properties, topography, and climatic conditions. Consequently, accurate land suitability evaluation is essential for optimizing agricultural production while maintaining environmental sustainability (Devaux *et al*., 2021; Koco *et al*., 2020). Volcanic regions are generally recognized as highly productive agricultural areas because volcanic ash contributes essential minerals that improve soil fertility. However, volcanic eruptions may also alter soil properties, increase erosion hazards, reduce nutrient retention, and create spatial variability in land quality. These changes may significantly affect crop performance and long-term land productivity. Therefore, post-eruption land evaluation has become an important component of sustainable agricultural planning in volcanic landscapes (Martínez *et a*l., 2021; Fajeriana & Korespondensi, 2024).

Mount Sinabung, located in North Sumatra, Indonesia, has experienced repeated eruptions since 2010, causing extensive environmental changes in surrounding agricultural lands. Previous studies have reported changes in soil fertility, physical properties, and agricultural productivity following volcanic eruptions. Nevertheless, most investigations have focused primarily on soil fertility restoration or general agricultural impacts, whereas comprehensive land suitability evaluation integrating land mapping units (LMUs), field observations, laboratory analyses, and actual–potential land suitability classification for potato cultivation remains limited (Aninda, 2022). Land suitability evaluation based on the FAO land evaluation framework provides a scientific approach for matching land characteristics with crop growth requirements. This approach enables the identification of limiting factors and supports the development of appropriate land management strategies to improve agricultural productivity (FAO, 1976; Fajeriana & Korespondensi, 2024). Furthermore, integrating Geographic Information Systems (GIS) with land suitability assessment facilitates spatial identification of suitable cultivation areas and provides valuable information for regional agricultural planning (Hapsari et al., 2014; Jayasinghe & Withanage, 2021). Although several studies have assessed soil conditions and agricultural recovery following the Mount Sinabung eruption, limited studies have comprehensively evaluated the actual and potential land suitability for potato cultivation using detailed land mapping units combined with field survey, laboratory analysis, and GIS-based spatial assessment. Consequently, scientific information regarding dominant limiting factors and feasible land improvement strategies remains insufficient. Recent studies have also highlighted that erosion hazards, nutrient retention, and topographic variability are among the principal determinants affecting sustainable potato cultivation in mountainous and volcanic regions (Singh et al., 2026; Koco et al., 2020). Therefore, integrated land evaluation is increasingly recognized as an effective tool for supporting evidence-based agricultural planning and climate-resilient farming systems (Devaux et al., 2021). The novelty of this study lies in the integration of GIS-based land mapping units, detailed soil characterization, and FAO matching techniques to evaluate both actual and potential land suitability for potato cultivation in post-eruption areas of Mount Sinabung. This study also identifies manageable and permanent limiting factors to formulate practical recommendations for sustainable potato cultivation in volcanic environments. Recent studies have emphasized that erosion hazard and terrain characteristics are important determinants in land suitability assessment for sustainable agriculture, particularly in mountainous environments. Therefore, this study aimed to evaluate the actual and potential land suitability for potato cultivation in post-eruption areas of Mount Sinabung and to identify the major limiting factors together with appropriate land management strategies for improving sustainable agricultural productivity (Devaux et al., 2021; Jayasinghe & Withanage, 2021; Singh et al., 2026).

MATERIALS AND METHODS

Study Area. This study was conducted from November 2025 to January 2026 in Naman Teran District, Karo Regency, North Sumatra, Indonesia. The study area is located approximately 20 km from Kabanjahe and 97 km from Medan, covering an area of 87.82 km² with elevations ranging from 700 to 1,400 m above sea level. The region experiences cool climatic conditions with average temperatures of approximately 16-17°C, making it one of the important highland agricultural areas for horticultural crop production. The study focused on agricultural land affected by the eruption of Mount Sinabung.

Land Mapping Unit Delineation. Land Mapping Units (LMUs) were generated using Geographic Information Systems (GIS) through the overlay of three thematic maps: soil type, elevation, and slope, each at a scale of 1:50,000. The overlay process produced thirteen LMUs representing different combinations of land

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characteristics. Among these, LMU 1 located in Sigarang-garang Village and LMU 2 located in Sukanalu Village were identified as the areas directly affected by the Mount Sinabung eruption and were selected for detailed evaluation.

Figure 1. Map of Naman Teran District

Field Survey and Soil Sampling

A reconnaissance survey was initially conducted to identify representative sampling locations and verify land characteristics. Subsequently, detailed field observations were carried out within each selected LMU. Soil samples were collected using an auger at a depth of 0–30 cm from representative sampling points and composited to obtain a homogeneous sample for laboratory analysis. In addition, soil profile observations were performed to a depth of approximately 120 cm to evaluate rooting conditions and soil morphological characteristics.

Field observations included drainage condition, slope, coarse fragments, effective soil depth, surface rock, rock outcrops, flooding hazard, and erosion severity. Geographic coordinates and elevation were recorded using a Global Positioning System (GPS) receiver and an altimeter.

Laboratory Analysis

Composite soil samples were analyzed at the Analytical Laboratory of PT Socfin Indonesia (SOCFINDO), Medan. The laboratory analyses included soil texture, pH (H_2O), cation exchange capacity (CEC), base saturation, soil organic carbon, salinity, and other soil properties required for land suitability evaluation. Laboratory procedures followed standard soil analytical methods commonly applied for agricultural land assessment.

Climate Data

Secondary climatic data covering the period 2015–2024 were obtained from the Meteorological, Climatological and Geophysical Agency (BMKG). Climatic variables included average air temperature, annual rainfall, relative humidity, and dry-month distribution. Climate classification was determined according to the Oldeman system and used as an input parameter in land suitability evaluation.

Land Suitability Evaluation

Land suitability was evaluated using the FAO Framework for Land Evaluation through the matching method, in which measured land characteristics were systematically compared with the ecological requirements of potato (*Solanum tuberosum* L.). Suitability classes were categorized into Very Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Not Suitable (N).

The evaluation considered several land qualities, including temperature, water availability, oxygen availability, rooting conditions, nutrient retention, erosion hazard, flooding hazard, toxicity, sodicity, and land preparation. Both actual and potential land suitability classes were determined by identifying the most limiting factor within each LMU.

Land Improvement Scenarios

Potential land suitability was estimated by considering feasible land improvement measures for manageable limiting factors. Recommended improvement practices included the application of organic amendments, liming, establishment of cover crops, and soil conservation measures to reduce erosion and improve nutrient retention. Limiting factors associated with climatic conditions and topography were regarded as permanent constraints because they cannot be substantially modified through land management interventions.

Data Analysis

Descriptive analysis was employed to summarize the characteristics of each LMU. Land suitability classification was performed using the limiting factor approach, whereby the final suitability class was determined by the most restrictive land characteristic. Spatial analysis and visualization of land suitability were conducted using GIS to produce thematic maps illustrating the distribution of suitability classes across the study area.

RESULTS AND DISCUSSION

Characteristics of the Study Area

The study area is located in Naman Teran District, Karo Regency, one of the main potato-producing regions situated at an elevation of from 700 to 1,400 m above sea level. Climatic observations indicated an average annual temperature of 20.1°C, annual rainfall of 1,779.8 mm, relative humidity of 87.8%, and Schmidt–Ferguson climate type B, representing a humid environment favorable for highland horticultural crops. Nevertheless, high rainfall combined with steep topography may accelerate surface runoff and soil erosion, thereby reducing soil quality and long-term agricultural productivity.

Spatial overlay of soil type, elevation, and slope maps generated thirteen Land Mapping Units (LMUs). However, only LMU 1 (Sigarang-garang Village) and LMU 2 (Sukanalu Village) were directly affected by the Mount Sinabung eruption and therefore became the focus of land suitability evaluation (Figure 2).

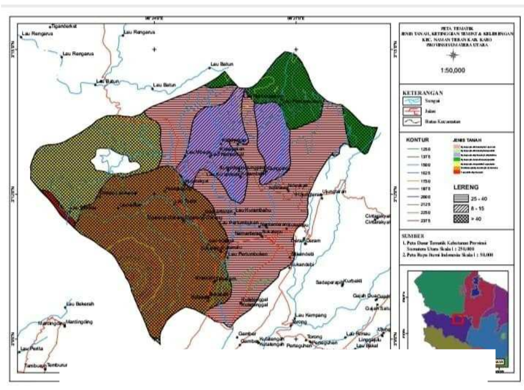

Figure 2. Land Mapping Units (LMUs)

Unlike many volcanic regions where newly deposited ash may initially enhance nutrient availability, repeated volcanic disturbances often produce heterogeneous soil conditions characterized by variable nutrient retention, unstable soil aggregates, and increased erosion susceptibility. Consequently, site-specific land evaluation is essential before determining appropriate agricultural land use.

Land Suitability Evaluation

The FAO matching approach revealed considerable differences in land suitability between the two eruption-affected land units. LMU 1 was classified as Not Suitable (N) under current conditions because severe erosion constituted the dominant limiting factor. In contrast, LMU 2 was categorized as Marginally Suitable (S3), primarily constrained by temperature and nutrient retention (Table1).

These findings demonstrate that land suitability in volcanic environments is controlled not only by inherent soil fertility but also by interactions among topography, climate, and post-eruption soil development. Although volcanic ash contributes essential minerals, steep slopes may accelerate nutrient losses through erosion, thereby reducing agricultural productivity if conservation measures are not implemented.

The results further indicate that land suitability evaluation should incorporate multiple environmental variables simultaneously rather than relying solely on soil fertility indicators. This integrated assessment provides a more reliable basis for sustainable land-use planning in post-eruption agricultural landscapes.

Table 1. Land Suitability for Potato (*Solanum tuberosum* L.) Cultivation in Naman Teran District, Karo Regency

	LMU 1 Sigarang-garang			LMU 2 Sukanalu		
Land characteristics	Data Value	Actual Land Suitability Class	Potential Land Suitability Class	Data Value	Actual Land Suitability Class	Potential Land Suitability Class
Temperature (tc) Mean Temperature (°C)	20,1	S3	S3	20,1	S3	S3
Water Availability **(wa)** Rainfall (mm) growing season	593	S2	S2	593	S2	S2

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Relative Humidity (%)	87,8	S1	S1	87,8	S1	S1
Oxygen Availability **(oa)** Drainage	Good/ Well drained	S1	S1	Good/ Well drained	S1	S1
Rooting Medium **(rc)** Texture	Sandy clay	S2	S2	Sandy clay	S2	S2
Coarse Fragments	< 15	S1	S1	< 15	S1	S1
Soil Depth (cm)	101	S1	S1	100	S1	S1
Nutrient Retention **(nr)** Clay CEC (cmol)	10,33	S2	S1	11,03	S2	S1
Base Saturation (%)	14,81	S2	S1	25,67	S2	S1
Soil pH (H_2O)	4,37	S3	S1	5,31	S2	S1
Organic Carbon (%)	1,9	S1	S1	0,47	S3	S1
Toxicity **(xc)** Salinity (dS/m)	0,4714	S1	S1	0,1823	S1	S1
Sodicity **(xn)** Exchangeable Sodium Percentage (ESP, %)	1,85	S1	S1	7,02	S1	S1
Erosion Hazard **(eh)** Slope (%)	25-40 %	N	S1	2-15 %	S2	S1
Erosion Hazard	Moderate	S2	S1	Moderate	S2	S1
Flood Hazard **(fh)** Flooding	F0	S1	S1	F0	S1	S1
Land Preparation **(lp)** Surface Rock Fragments (%)	5-15	S2	S2	15-40	S3	S3
Rock Outcrops (%)	5-15	S2	S2	5-15	S2	S2
Actual Land Suitability		N (eh)		S3 (tc, nr)		
Potential Land Suitability		S3 (tc)		S3 (tc, lp)		

Limiting Factors in LMU 1

The principal limiting factor identified in LMU 1 was erosion hazard associated with steep slopes. Excessive erosion promotes the removal of nutrient-rich topsoil, decreases soil organic matter, weakens aggregate stability, and limits root development. These conditions substantially reduce potato productivity because tuber initiation and enlargement require loose, fertile, and well-structured soils (FAO, 1976; Koco et al., 2020; Singh et al., 2026).

Following the implementation of proposed management practices, including organic matter application, liming, and cover crop establishment, land suitability improved from class N to class S3. These practices contribute to increasing aggregate stability, improving soil structure, enhancing infiltration, and reducing runoff intensity. Consequently, erosion becomes less restrictive, while temperature remains the only dominant limiting factor (Ritung et al., 2011; Fajeriana & Korespondensi, 2024; Singh et al., 2026).

The persistence of temperature as a limiting factor indicates that climatic constraints cannot be modified through conventional land management. Therefore, adaptive strategies such as selecting suitable potato cultivars and optimizing planting schedules may represent more realistic alternatives than attempting environmental modification (Devaux et al., 2021; Martínez *et al*., 2021; FAO, 1976).

The finding that erosion hazard was the dominant limiting factor in LMU 1 is consistent with Singh et al. (2026), who reported that steep slopes substantially increase soil erosion and reduce agricultural land suitability in mountainous environments.

Similarly, Koco *et al*. (2020) observed that soil physical properties and drainage strongly influence potato productivity, supporting the present findings.

Limiting Factors in LMU 2

In LMU 2, marginal suitability was primarily associated with low nutrient retention and suboptimal temperature conditions. Nutrient retention reflects the soil's capacity to retain essential nutrients against leaching losses. Under high-rainfall conditions, soils with relatively low cation exchange capacity and limited organic matter generally experience greater nutrient depletion, thereby reducing fertilizer-use efficiency (FAO, 1976; Ritung et al., 2011; Fajeriana & Korespondensi, 2024).

Application of organic amendments is expected to improve cation exchange capacity, enhance microbial activity, increase soil organic carbon, and strengthen nutrient cycling. Nevertheless, despite improvements in soil fertility, land suitability remained within class S3 because land preparation constraints became increasingly important due to abundant surface rock fragments and rock outcrops (Koco *et al*., 2020; Devaux et al., 2021; Ritung *et al*., 2011).

These findings emphasize that successful land management requires simultaneous improvement of soil fertility and physical land conditions. In volcanic landscapes, nutrient management alone is insufficient if mechanical limitations continue to restrict cultivation activities (Martínez et al., 2021; Devaux et al., 2021; Azmi & Sunarno, 2021). Our results differ from Martínez *et al*. (2021), who found that volcanic ash soils maintained higher moisture retention despite reduced nutrient availability.

Relationship Between Climate and Land Suitability

Climate exerted substantial influence on the observed land suitability classes. Potato generally performs best under cool temperatures and adequate moisture conditions. Although the elevation of Naman Teran provides relatively favorable thermal conditions, the average annual temperature still constituted a limiting factor according to FAO suitability criteria (FAO, 1976; Devaux et al., 2021; Martínez et al., 2021).

Furthermore, abundant rainfall contributes positively to water availability but simultaneously increases erosion risk and nutrient leaching. Therefore, climatic variables indirectly influence land suitability through their effects on soil degradation processes. These interactions highlight the importance of integrating climatic information into agricultural land evaluation for sustainable crop production (Singh *et al*., 2026; FAO, 1976; Ritung *et al*., 2011).

Implications for Sustainable Land Management

This study demonstrates that volcanic landscapes should not automatically be regarded as highly suitable agricultural areas despite their generally fertile parent materials. Site-specific evaluation remains essential because post-eruption environmental conditions generate considerable spatial variability in land quality (Azmi & Sunarno, 2021; Martínez *et al*., 2021; Fajeriana & Korespondensi, 2024).

The integration of Geographic Information Systems (GIS), field observations, laboratory analyses, and FAO land suitability evaluation provides a robust framework for identifying manageable and permanent limiting factors. From a practical perspective, erosion control, organic matter management, and conservation agriculture should be prioritized in areas with severe degradation, whereas long-term planning should consider climatic limitations and topographic constraints when allocating land for potato cultivation (Hapsari et al., 2014; Jayasinghe & Withanage, 2021; FAO, 1976; Ritung et al., 2011).

These findings contribute scientific evidence supporting sustainable agricultural development in post-volcanic regions and provide a practical basis for regional land-use planning and climate-resilient potato production systems (Devaux et al., 2021; Jayasinghe & Withanage, 2021; Azmi & Sunarno, 2021). The contribution of this study lies in applying GIS-based LMUs integrated with the FAO framework to evaluate both actual and potential land suitability in the post-eruption area of Mount Sinabung.

Statement on the Use of Artificial Intelligence

The authors declares that artificial intelligence (AI) was used in a limited capacity to improve language quality and clarity. All ideas, analyses, and conclusions are the author's own and have been independently verified in accordance with academic standards.

CONCLUSION

This study demonstrated that Geographic Information System (GIS)-based land suitability evaluation combined with the FAO matching approach provides an effective framework for assessing the suitability of potato (*Solanum tuberosum* L.) cultivation in the post-eruption area of Mount Sinabung, Naman Teran District, Karo Regency. Spatial analysis identified thirteen Land Mapping Units (LMUs), with LMU 1 (Sigarang-garang Village) and LMU 2 (Sukanalu Village) representing the areas directly affected by volcanic eruptions.

The evaluation revealed that LMU 1 was classified as Not Suitable (N) under current conditions because of severe erosion hazards. Following the implementation of recommended land improvement measures, including organic matter application, liming, and cover cropping, the land suitability improved to Marginally Suitable (S3), with temperature becoming the primary limiting factor. In contrast, LMU 2 was classified as Marginally Suitable (S3) under both actual and potential conditions. Although improvements in nutrient retention were achievable through appropriate soil management, land preparation constraints associated with surface rock and rock outcrops remained important limiting factors alongside temperature.

Overall, the study indicates that erosion hazard and nutrient retention are manageable constraints that can be substantially improved through appropriate soil conservation and fertility management practices. Conversely, climatic conditions, particularly temperature, and certain topographic characteristics represent relatively permanent limiting factors that require adaptive rather than corrective management strategies.

The principal scientific contribution of this study lies in the integration of GIS-based Land Mapping Units, detailed field observations, laboratory soil analyses, and the FAO land evaluation framework to determine both actual and potential land suitability in a post-eruption volcanic landscape. This integrated approach provides more comprehensive information for identifying dominant limiting factors and formulating site-specific land management recommendations than conventional descriptive land assessment.

From a practical perspective, the findings provide valuable scientific evidence for supporting sustainable potato cultivation, regional agricultural planning, and land rehabilitation in volcanic environments affected by natural disturbances. Future studies are recommended to incorporate high-resolution spatial analysis, remote sensing techniques, and multi-criteria decision analysis to improve the accuracy of land suitability evaluation and strengthen climate-resilient agricultural development in volcanic regions.

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